Status and New Opportunities in Neutrino Physics

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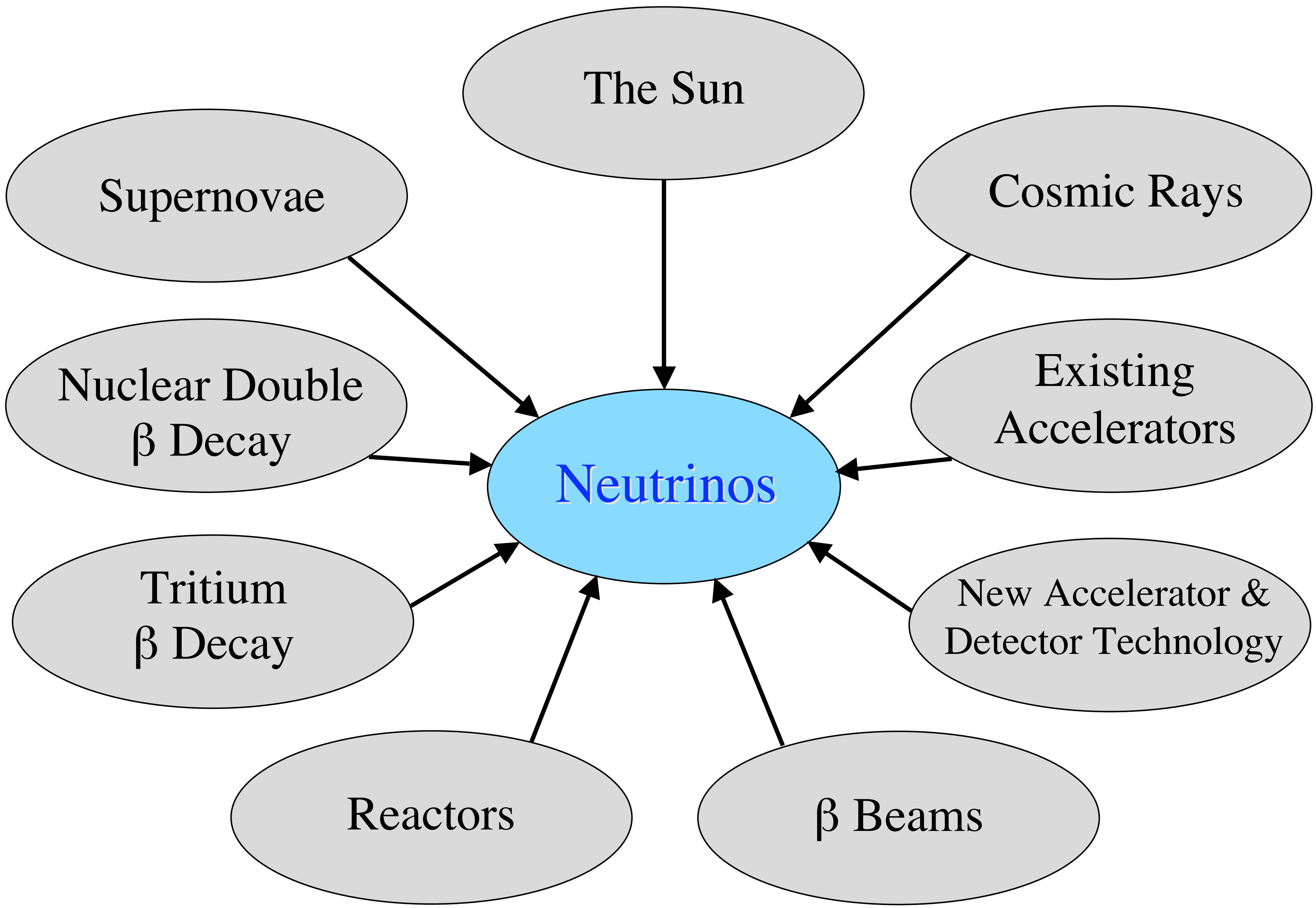
Neutrinos and photons are, by far, the most abundant particles in the universe.

The study of neutrinos involves —

- Astrophysics
- Nuclear physics
- Particle physics
- Accelerator and detector technology


The Sun
Supernovae
Cosmic Rays
Nuclear Double
β Decay
Neutrinos
Existing
Accelerators
Tritium
β Decay
New Accelerator &
Detector Technology
Reactors
β Beams

Solar Neutrinos

History –

Nuclear reactions in the core of the sun produce ν_e. Only ν_e.

Theorists, especially John Bahcall, calculated the produced ν_e flux vs. energy E.

Ray Davis' Homestake experiment measured the higher-E part of the ν_e flux ϕ_{ν_e} that arrives at earth.

The Homestake experiment could detect only ν_e. It found:

$$\frac{\phi_{\nu_e}(\text{Homestake})}{\phi_{\nu_e}(\text{Theory})} = 0.34 \pm 0.06$$

The Possibilities:

The theory was wrong.

The experiment was wrong.

Both were wrong.

Neither was wrong. Two thirds of the ν_e flux morphs into a flavor or flavors that the Homestake experiment could not see.

The Resolution —

Sudbury Neutrino Observatory (SNO) measures, for the high-energy part of the solar neutrino flux:

$$\nu_{sol}\, d \rightarrow e\, p\, p \;\Rightarrow \phi_{\nu_e}$$

$$\nu_{sol}\, d \rightarrow \nu\, n\, p \;\Rightarrow \phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$$

From the two reactions,

$$\frac{\phi_{\nu_e}}{\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}} = 0.340 \pm 0.023\,(\text{stat}) \pm 0.030\,(\text{syst})$$

Clearly, $\phi_{\nu_\mu} + \phi_{\nu_\tau} \neq 0$. Neutrinos change flavor.

SNO: $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau} = (4.94 \pm 0.21 \pm 0.36) \times 10^6/\text{cm}^2\text{sec}$

Theory*: $\phi_{\text{total}} = (5.69 \pm 0.91) \times 10^6/\text{cm}^2\text{sec}$

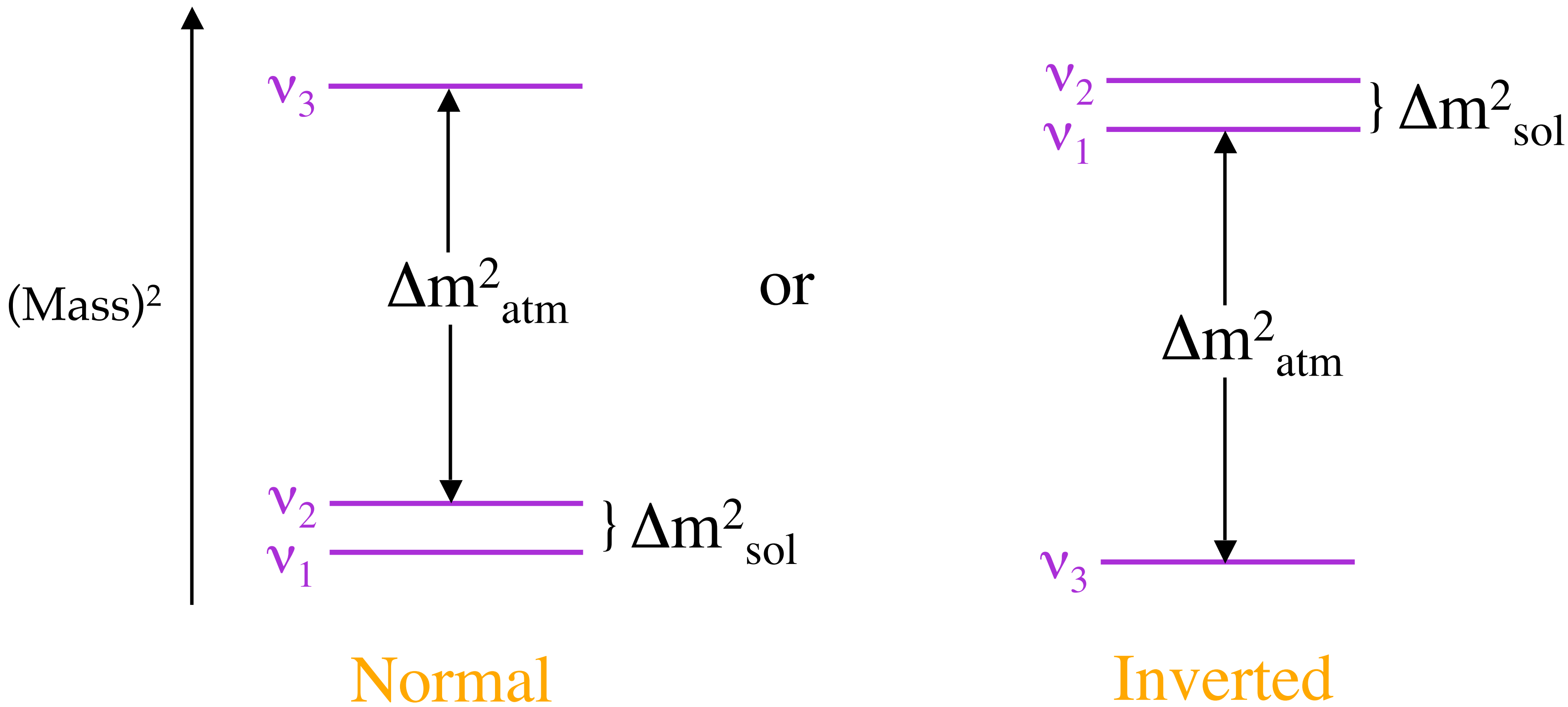
*Bahcall, Basu, Serenelli

John Bahcall and Ray Davis both stuck to their guns for several decades, and both were right all along.

Change of neutrino flavor implies neutrino mass.

What We Have Learned

The (Mass)^2 Spectrum



$\Delta m^2_{sol} \cong 8 \times 10^{-5}$ eV^2, $\quad \Delta m^2_{atm} \cong 2.5 \times 10^{-3}$ eV^2

Are there *more* mass eigenstates, as LSND suggests?

Leptonic Mixing

$\ell_e \equiv e,\ \ell_\mu \equiv \mu,\ \ell_\tau \equiv \tau$

When $W^+ \to \ell_\alpha^{\ +} + \nu_\alpha$,

e, μ, or τ

the produced neutrino state $|\nu_\alpha\rangle$ is

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}\,|\nu_i\rangle\ .$$

Neutrino of flavor α

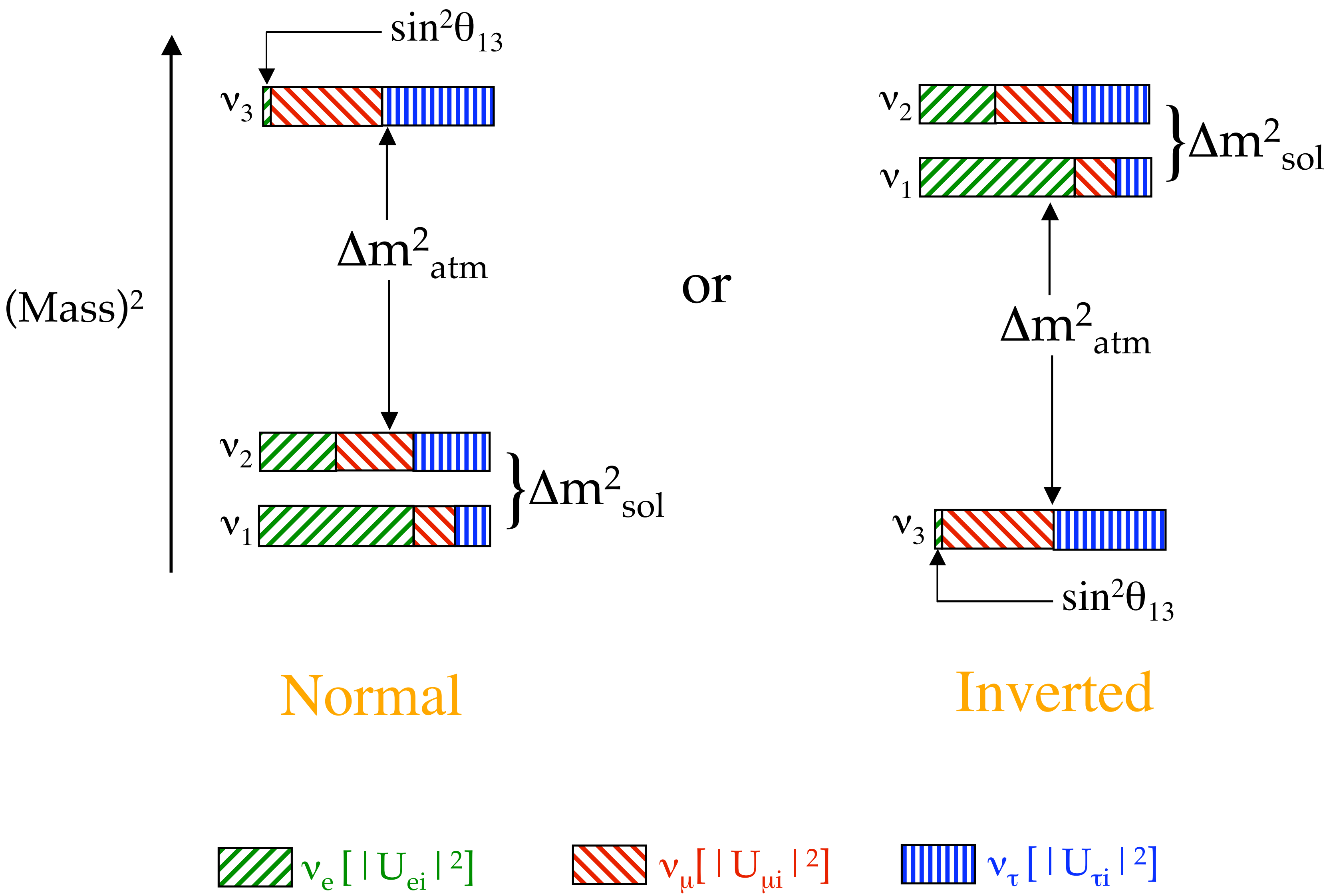
Neutrino of definite mass m_i

Unitary Leptonic Mixing Matrix

Inverting: $|\nu_i\rangle = \sum_i U_{\alpha i}\,|\nu_\alpha\rangle$.

Flavor-α fraction of $\nu_i = |U_{\alpha i}|^2$.

The spectrum, showing its approximate flavor content, is



The Mixing Matrix

$$U = \overset{\text{Atmospheric}}{\begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}} \times \overset{\text{Cross-Mixing}}{\begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix}} \times \overset{\text{Solar}}{\begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

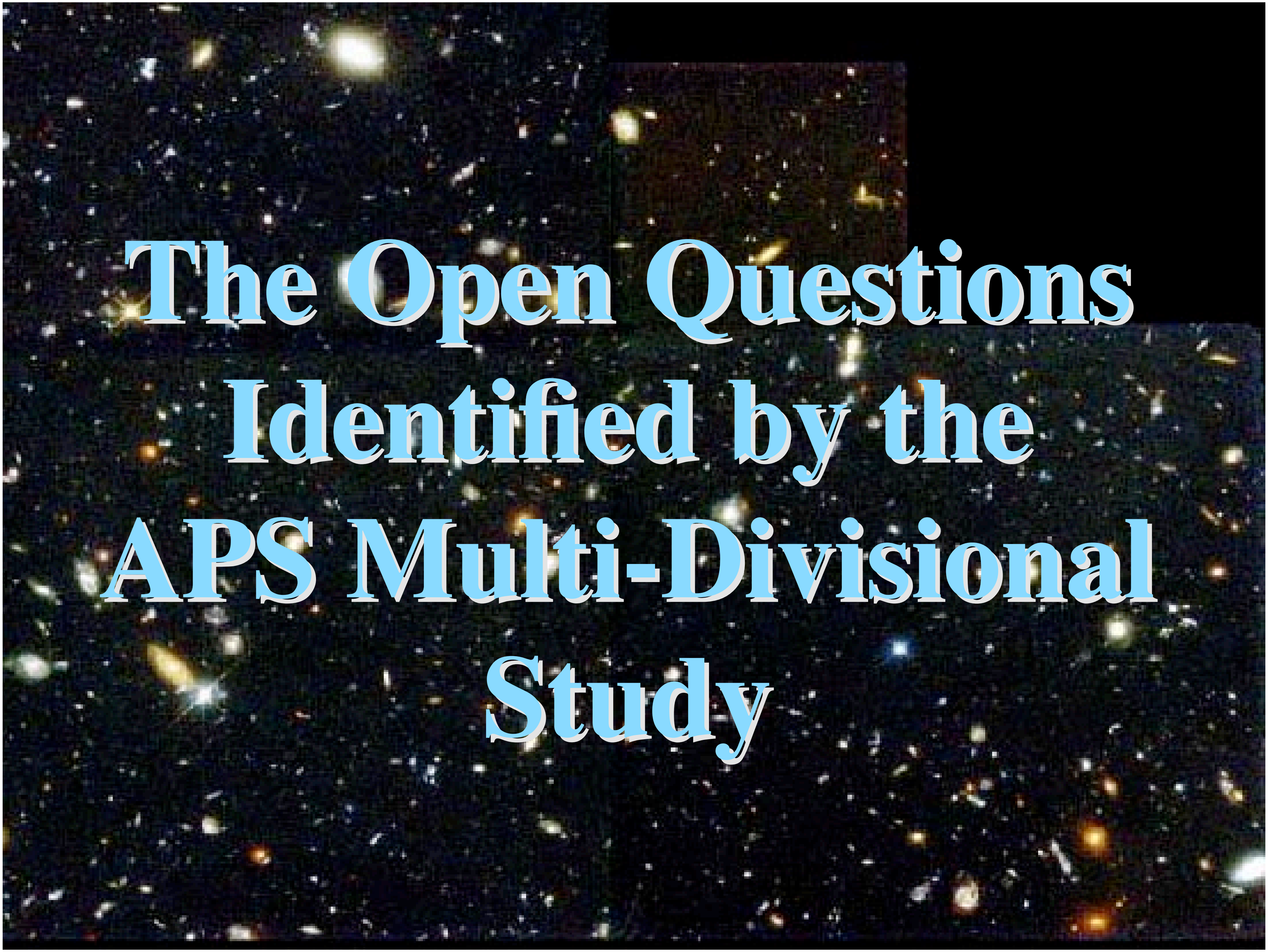
$$\times \underset{\text{Majorana } \cancel{CP} \text{ phases}}{\begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}}$$

$c_{ij} \equiv \cos\theta_{ij}$
$s_{ij} \equiv \sin\theta_{ij}$

$\theta_{12} \approx \theta_{sol} \approx 34°$, $\theta_{23} \approx \theta_{atm} \approx 37\text{-}53°$, $\theta_{13} \lesssim 10°$

δ would lead to $P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) \neq P(\nu_\alpha \to \nu_\beta)$. $\cancel{CP}$

But note the crucial role of $s_{13} \equiv \sin\theta_{13}$.


The Open Questions
Identified by the
APS Multi-Divisional
Study

Neutrinos and the New Paradigm

- What are the masses of the neutrinos?

  Is the spectrum like  or  ?

- What is the pattern of mixing among the different types of neutrinos?

  What is θ_{13}? Is θ_{23} maximal?

•Are neutrinos their own antiparticles?

•Do neutrinos violate the symmetry CP? Is
$P(\overline{\nu_\alpha} \rightarrow \overline{\nu_\beta}) \neq P(\nu_\alpha \rightarrow \nu_\beta)$?

Neutrinos and the Unexpected

- Are there “sterile” neutrinos?

- Do neutrinos have unexpected or exotic properties?

We must be alert to further surprises.

- What can neutrinos tell us about the models of new physics beyond the Standard Model?

The See-Saw Mechanism relates ν masses to physics at the high-mass scale where the forces become unified.

A signature feature of the See-Saw is that $\bar{\nu} = \nu$.

Neutrinos and the Cosmos

- What is the role of neutrinos in shaping the universe?
- Is CP violation by neutrinos the key to understanding the matter – antimatter asymmetry of the universe?
- What can neutrinos reveal about the deep interior of the earth and sun, and about supernovae and other ultra high energy astrophysical phenomena?


How the
Questions May Be
Answered

Are Neutrinos Their Own Antiparticles?

Does —

- $\overline{\nu_i} = \nu_i$ (Majorana neutrinos)

or

- $\overline{\nu_i} \neq \nu_i$ (Dirac neutrinos) ?

$e^+ \neq e^-$ since Charge(e^+) = – Charge(e^-).

But neutrinos may not carry any conserved charge-like quantum number.

A conserved Lepton Number L defined by—
$L(\nu) = L(\ell^-) = -L(\overline{\nu}) = -L(\ell^+) = 1$ may not exist.

If it does not, then nothing distinguishes $\overline{\nu}_i$ from ν_i . We then have Majorana neutrinos.

Why Many Theorists Think L Is Not Conserved

The Standard Model (SM) is defined by the fields it contains, its symmetries (notably Weak Isospin Invariance), and its renormalizability.

Anything allowed by the symmetries occurs in nature.

The SM contains no ν mass, and no ν_R field, only ν_L.

This SM conserves the lepton number L.

But now we know the neutrino has mass.

If we try to preserve L, we accommodate this mass by adding a Dirac, L - conserving, mass term: $m_D\overline{\nu}_L\nu_R$.

To add a Dirac mass term, we had to add ν_R to the SM.

Unlike ν_L , ν_R carries no Weak Isospin.

Thus, no SM symmetry prevents the occurrence of the Majorana mass term $m_M \overline{\nu_R{}^c} \nu_R$.

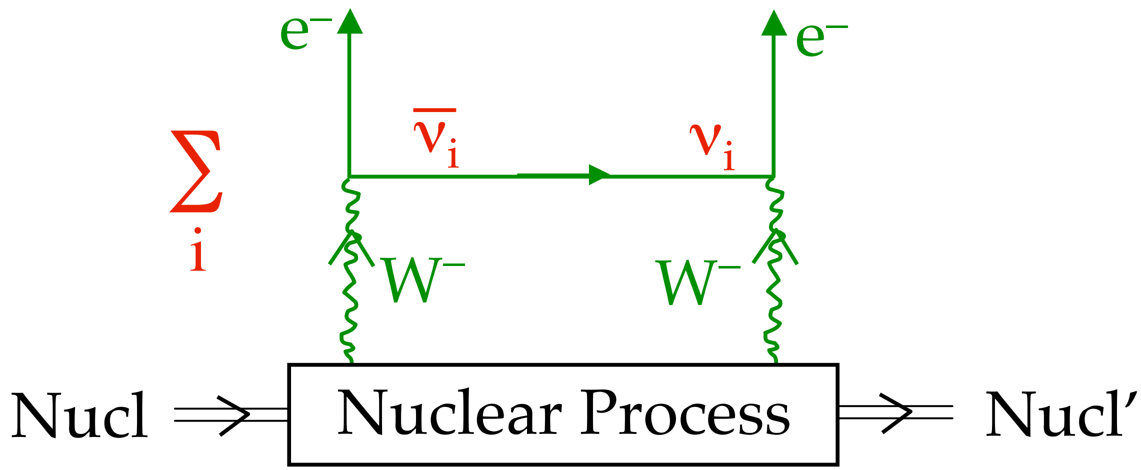
This mass term causes $\nu \rightarrow \overline{\nu}$. It does not conserve L.

If anything allowed by the *extended* SM occurs in nature, then L is not conserved.

If the nonconservation of L comes from Majorana ***masses***, any attempt to find it must overcome the smallness of neutrino masses.

To Demonstrate That $\overline{\nu_i} = \nu_i$:

Neutrinoless Double Beta Decay [$0\nu\beta\beta$]



By avoiding competition, this process can cope with the small neutrino masses.

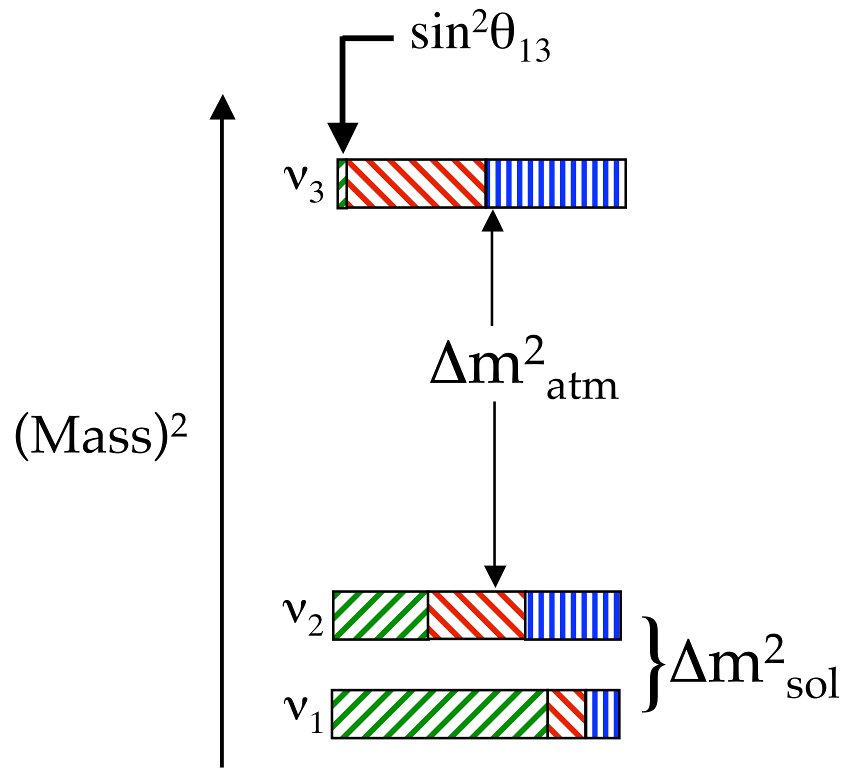
Observation would imply $\not{L}$ and $\overline{\nu}_i = \nu_i$.

In Pursuit of θ_{13}

Both CP violation and our ability to tell whether the spectrum is normal or inverted depend on θ_{13}.

If $\sin^2 2\theta_{13} < 0.01$, a neutrino factory will be needed to study both of these issues.

How may θ_{13} be measured?



$\sin^2\theta_{13} = |U_{e3}|^2$ is the small ν_e piece of ν_3.

ν_3 is at one end of Δm^2_{atm}.

$\therefore$ We need an experiment with L/E sensitive to Δm^2_{atm} (L/E ~ 500 km/GeV) , and involving ν_e.

Complementary Approaches

Reactor Experiments

Reactor $\bar{\nu}_e$ disappearance while traveling L ~ 1.5 km. This process depends on θ_{13} alone:

$$P(\bar{\nu}_e \text{ Disappearance}) =$$

$$= \sin^2 2\theta_{13} \sin^2[1.27\Delta m^2_{atm}(eV^2)L(km)/E(GeV)]$$

Accelerator Experiments

Accelerator $\nu_\mu \rightarrow \nu_e$ while traveling L > Several hundred km. This process depends on θ_{13}, θ_{23}, on whether the spectrum is normal or inverted, and on whether CP is violated through the phase δ.

Analytic Approximations

- $\Delta = \Delta m^2_{31} L/4E$
- qualitative understanding $\Rightarrow$ expand in $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2 2\theta_{13}$
- matter effects $\hat{A} = A/\Delta m^2_{31} = 2VE/\Delta m^2_{31};\ V = \sqrt{2} G_F n_e$

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \quad \approx \quad & \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
\pm \quad & \sin \delta_{CP}\ \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+ \quad & \cos \delta_{CP} \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
+ \quad & \alpha^2 \sin^2 2\theta_{12} \cos^2 \theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

(Lindner)

The Mass Spectrum:  or  ?

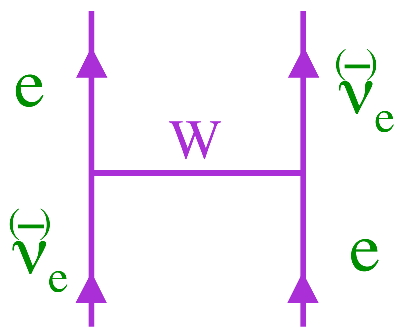
Generically, grand unified models (GUTS) favor —

GUTS relate the Leptons to the Quarks.

 is un-quark-like, and would probably involve a lepton symmetry with no quark analogue.

How To Determine If The Spectrum Is Normal Or Inverted

Exploit the fact that, in matter,



raises the effective mass of ν_e, and lowers that of $\bar{\nu}_e$.

This changes both the spectrum and the mixing angles.

Matter effects grow with energy E.

At E ~ 1 GeV, matter effects ⇒

$$\sin^2 2\overset{(\overline{\ \ })}{\theta}_M \cong \sin^2 2\theta_{13}\left[\,1 \underset{(-)}{+} S\,\frac{E}{6\ \mathrm{GeV}}\,\right].$$

$\mathrm{Sign}[m^2(\text{—}) - m^2(=)]$

At oscillation maximum,

$$\frac{P(\nu_\mu \to \nu_e)}{P(\bar{\nu}_\mu \to \bar{\nu}_e)} \begin{cases} >1 \ ; \\ <1 \ ; \end{cases}$$

Note fake CP violation.

The effect is $\begin{cases} 30\% \ ; \ E = 2 \ \mathrm{GeV}\ (\mathrm{NuMI}) \\ 10\% \ ; \ E = 0.7\ \mathrm{GeV}\ (\mathrm{T2K}) \end{cases}$

T2K cannot address the mass hierarchy. (Feldman)

Larger E is better.

But want L/E to correspond roughly to the peak of the oscillation.

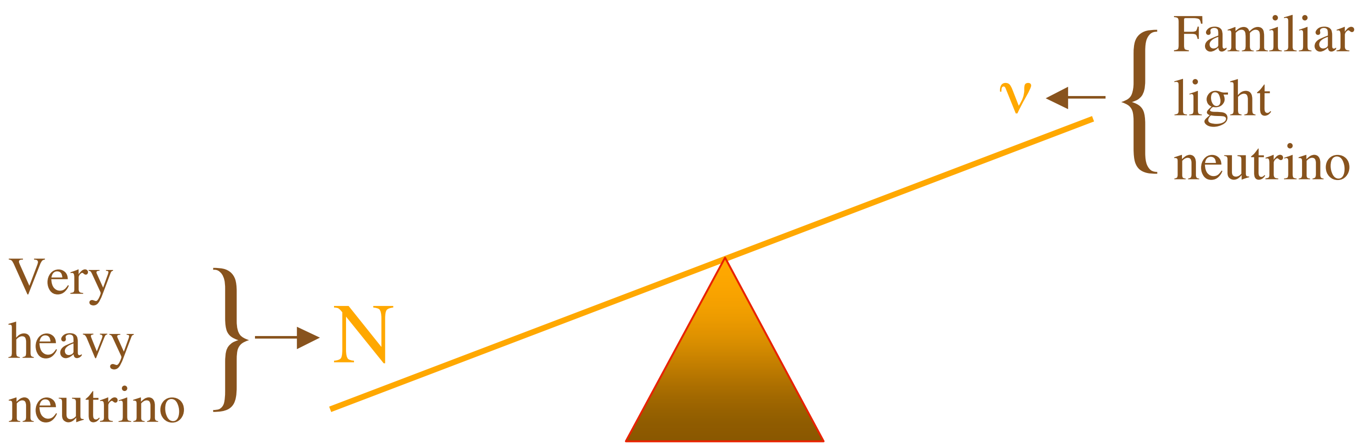
Therefore, larger E should be matched by larger L.

Using larger L to determine whether the spectrum is normal or inverted could be a special contribution of the U.S. to the global program.

Why would $\not{C}\!\not{P}$ in ν oscillation be interesting?

The most popular theory of why neutrinos are so light is the —

See-Saw Mechanism



The heavy neutrinos N would have been made in the hot Big Bang.

The heavy neutrinos N, like the light ones ν, are Majorana particles. Thus, an N can decay into ℓ^- or ℓ^+.

If neutrino oscillation violates CP, then quite likely so does N decay.

Then, in the early universe, we would have had different rates for the CP-mirror-image decays –

$$N \rightarrow \ell^- + \ldots \qquad \text{and} \qquad N \rightarrow \ell^+ + \ldots$$

This would have led to unequal numbers of leptons and antileptons (Leptogenesis).

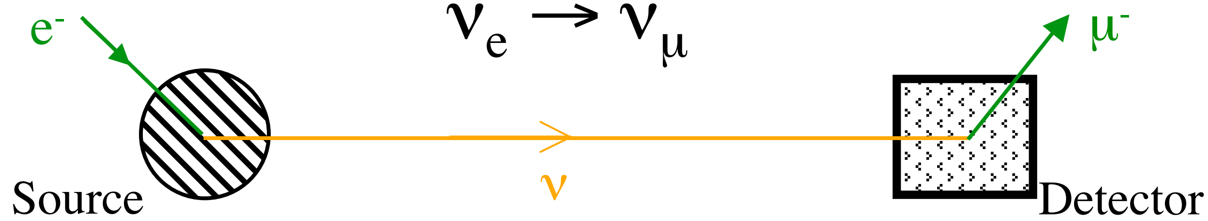
Perhaps this was the original source of the present preponderance of Matter over Antimatter in the universe.

How To Search for $\cancel{CP}$

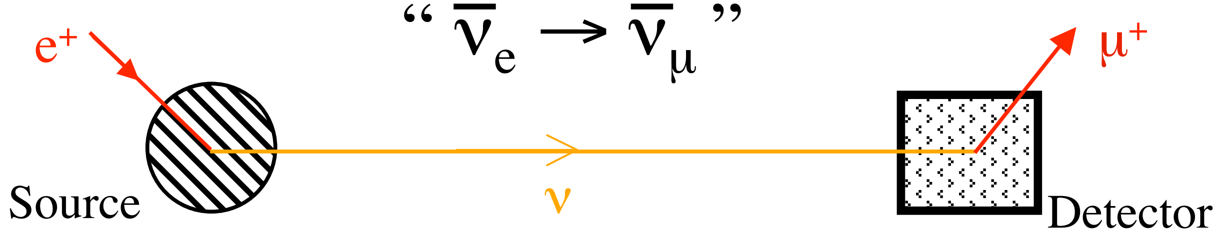
Look for $P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \neq P(\nu_\alpha \rightarrow \nu_\beta)$

"$\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$" is a different process from $\nu_\alpha \rightarrow \nu_\beta$ even when $\bar{\nu}_i = \nu_i$

$\nu_e \rightarrow \nu_\mu$



"$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$"



The NuMI – T2K Relationship

Eventually, the $\not{C}\not{P}$ and matter-effect sources of any $\nu - \bar{\nu}$ asymmetry must be disentangled.

	Distance L	Energy E
NuMI	800 km	2 GeV
T2K	300 km	0.7 GeV

Owing to its higher E, the NuMI experiments will have a three-fold bigger matter effect.

Combining the NuMI and T2K results will greatly facilitate the separation of $\not{C}\not{P}$ from matter effects.

The Future: The Proton Driver and Large Detector

These facilities, or their equivalents, are needed if we are to be able to determine whether the spectrum is normal or inverted, and to observe CP violation, for any $\sin^2 2\theta_{13} > (0.01 - 0.02)$.

Neutrino Factories and β Beams

The ultimate in sensitivity, with intense, flavor-pure beams.

Neutrino Factory: A muon storage ring, producing neutrinos via —

Doesn't make μ^-

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

β Beam: A boosted-radioactive-ion storage ring, producing neutrinos via —

$$^{18}Ne \rightarrow {}^{18}F + e^+ + \nu_e$$

Monoenergetic ν_e from e^- capture

Then look for $\nu_e \rightarrow \nu_\mu$

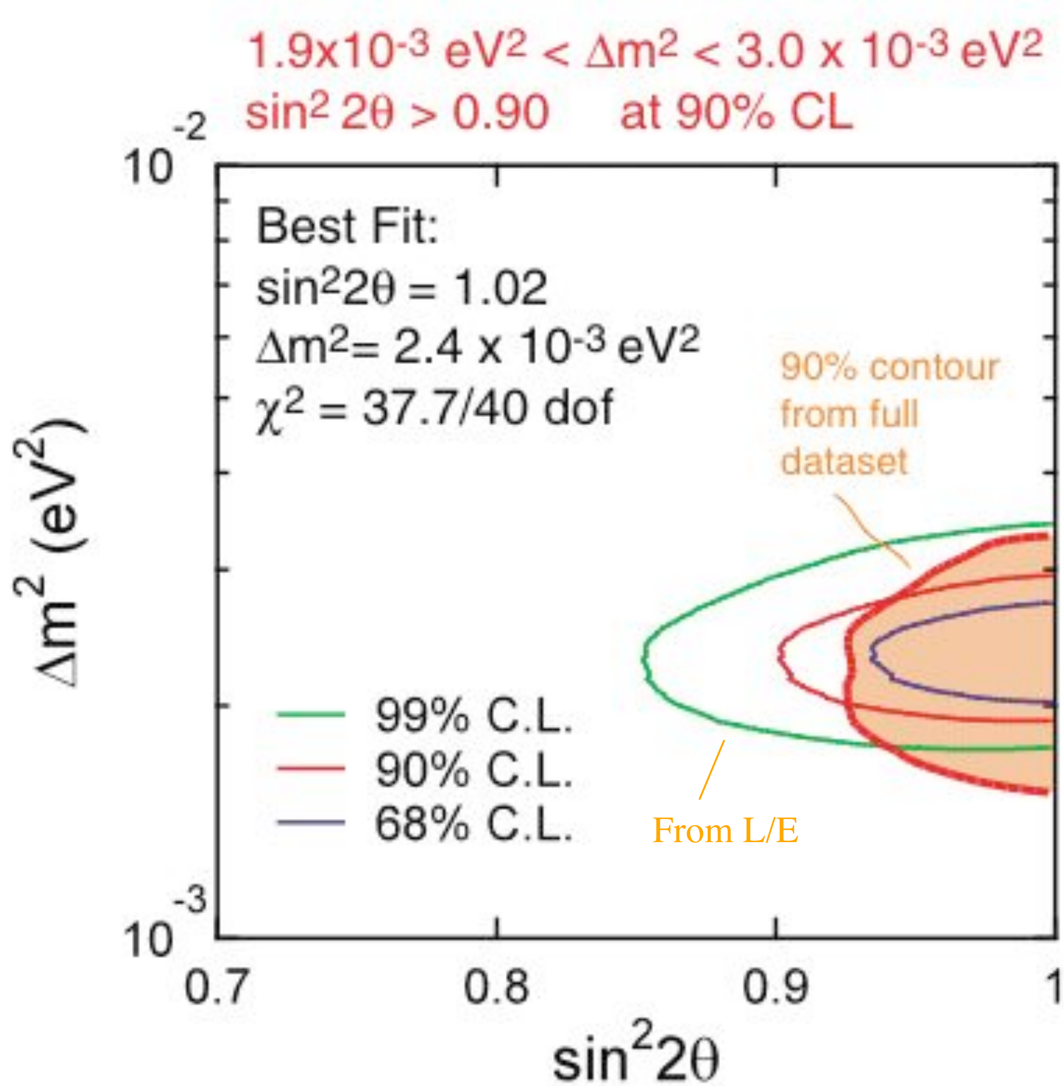
Conclusion

We have a very rich opportunity to do exciting physics.

Neutrino physics has connections to astrophysics and cosmology, and to both nuclear and particle physics.

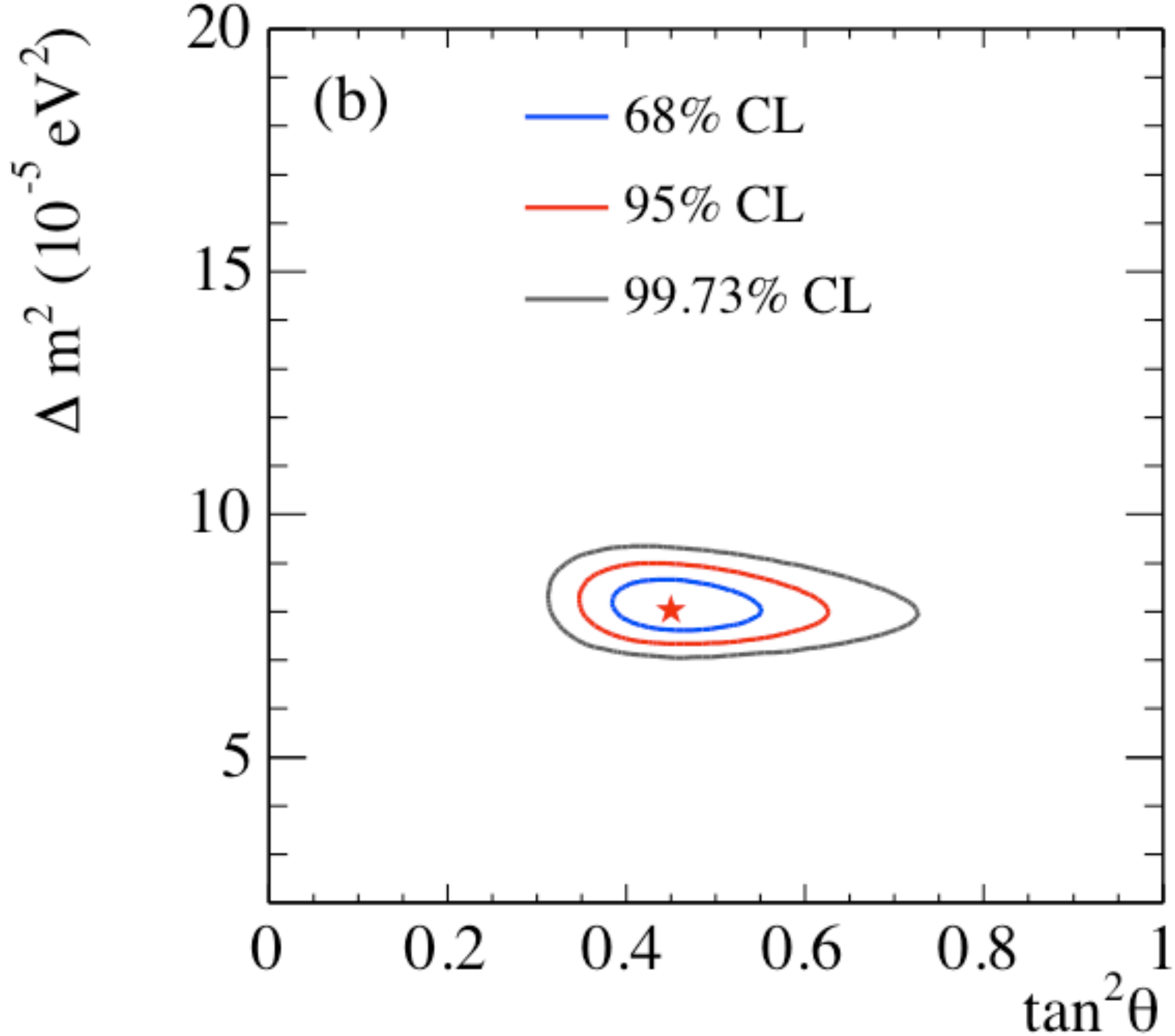
Answering the questions raised by the discovery of neutrino mass should prove **very** interesting!

BACKUP SLIDES



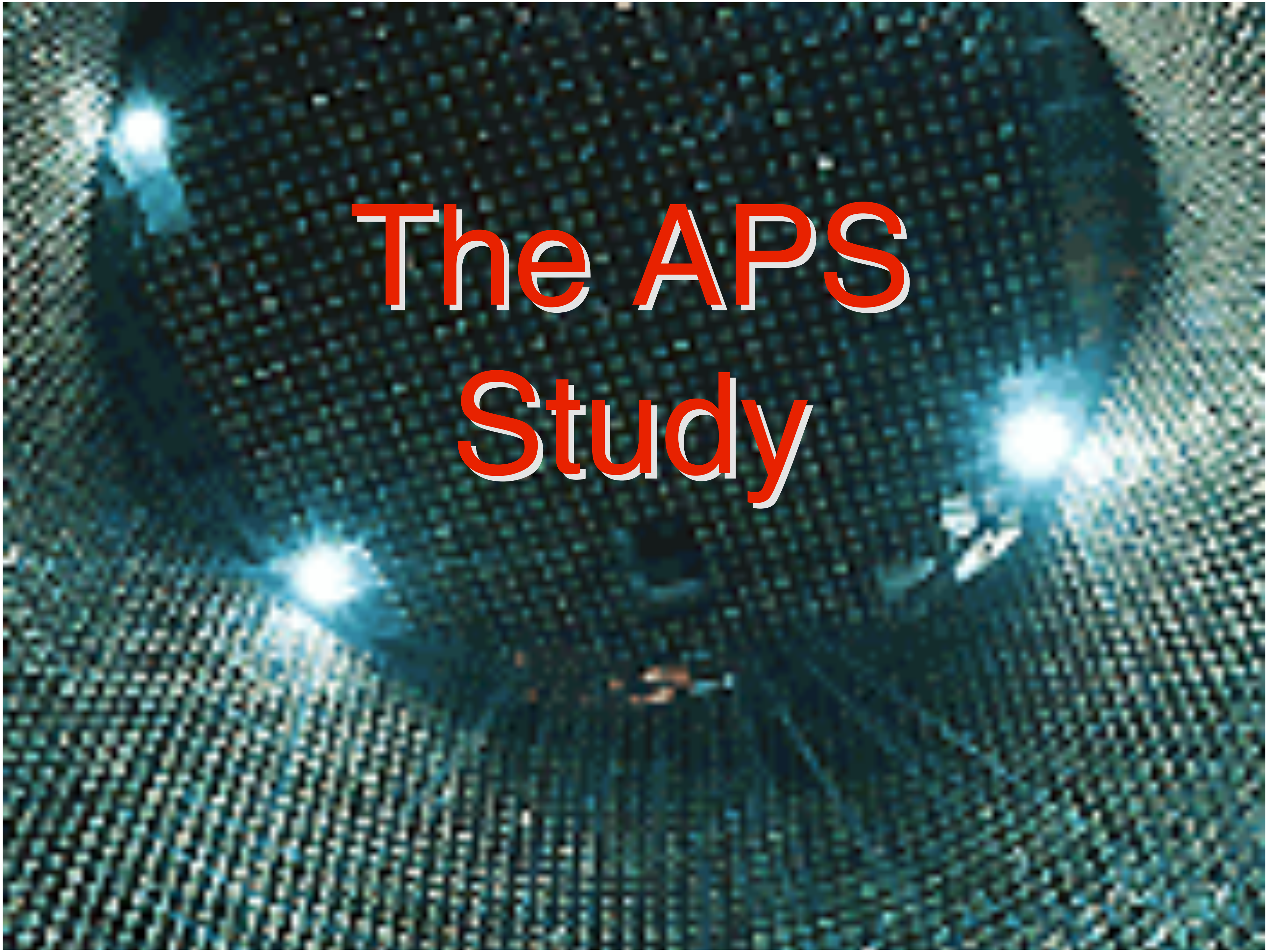
From Y. Suzuki at Lepton - Photon 2005

Atmospheric Δm^2 and mixing angle from SuperKamiokande L/E analysis and full data set



From nucl-ex/ 0502021

Solar Δm^2 and mixing angle from SNO analysis of solar neutrino and KamLAND data


The APS
Study

The discovery of
neutrino mass and mixing

⇓

Open questions about neutrinos and
their connections to other physics

⇓

Need for a coherent strategy
for getting answers

A year-long study of the future of neutrino physics, sponsored by the American Physical Society Divisions of –

Nuclear Physics

Particles and Fields

Astrophysics

Physics of Beams

The APS Multi-Divisional Neutrino Study

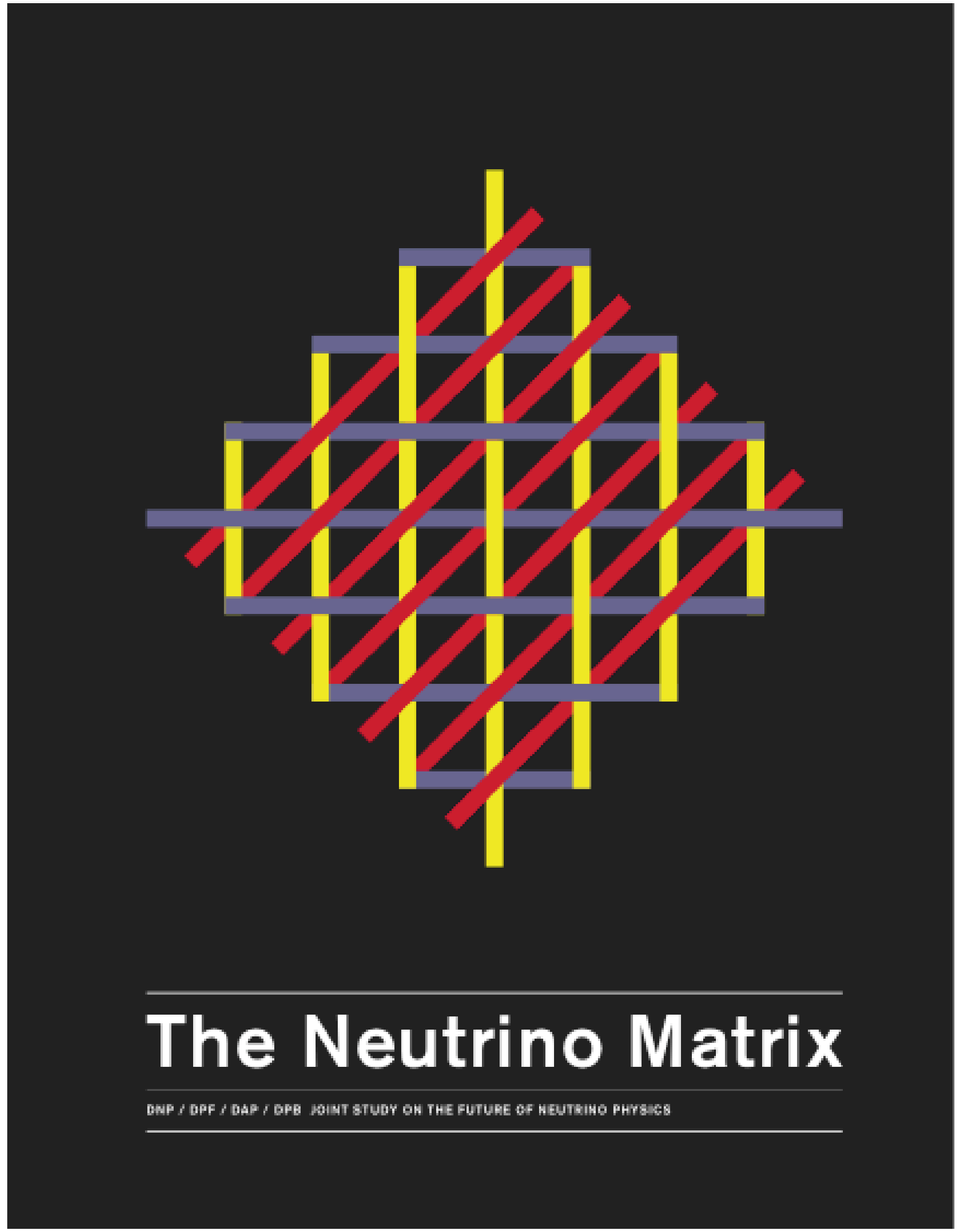
- Over 200 Participants
- Seven Working Groups
- Organizing Committee: Janet Conrad, Guido Drexlin, Belen Gavela, Takaaki Kajita, Paul Langacker, Keith Olive, Bob Palmer, Georg Raffelt, Hamish Robertson, Stan Wojcicki, Lincoln Wolfenstein
- Co-Chairpersons: Stuart Freedman, Boris Kayser

The aim: To develop a strategy for the U.S. role in a global neutrino program.

The U.S. effort should complement, and cooperate with, the efforts in Europe and Asia.

Our Main Report,
The Neutrino Matrix,
and the reports of the Working Groups, may be found at –

www.aps.org/neutrino

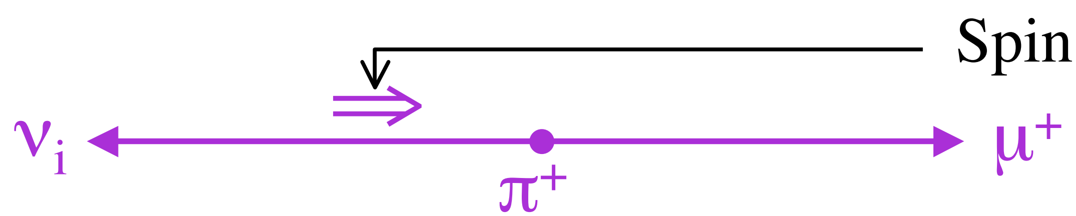


How Can We Demonstrate That $\bar{\nu}_i = \nu_i$?

We assume neutrino interactions are correctly described by the SM. Then the interactions conserve L ($\nu \to \ell^-$; $\bar{\nu} \to \ell^+$).

An Idea that Does Not Work
[and illustrates why most ideas do not work]

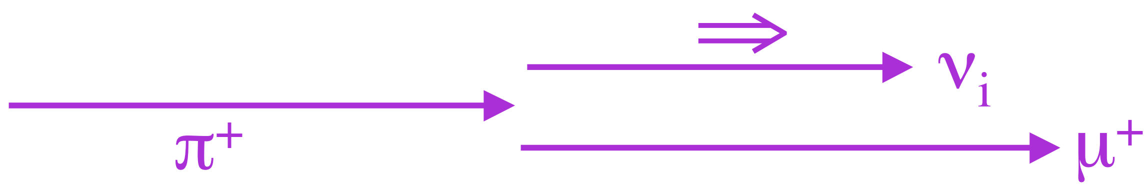
Produce a ν_i via—



Pion Rest Frame

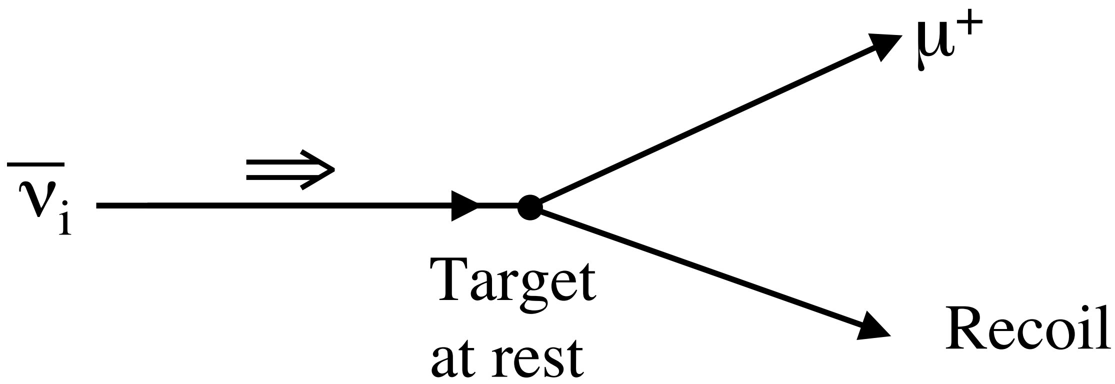
Give the neutrino a Boost:

β_π(Lab) > β_ν(π Rest Frame)



Lab. Frame

The SM weak interaction causes—



$\nu_i = \overline{\nu}_i$ means that $\nu_i(h) = \overline{\nu}_i(h)$.

helicity

If $\nu_i \xrightarrow{\Rightarrow} = \overline{\nu}_i \xrightarrow{\Rightarrow}$,

our $\nu_i \xrightarrow{\Rightarrow}$ will make μ^+ too.

Minor Technical Difficulties

$$\beta_\pi(\text{Lab}) > \beta_\nu(\pi \text{ Rest Frame})$$

$$\Rightarrow \frac{E_\pi(\text{Lab})}{m_\pi} > \frac{E_\nu(\pi \text{ Rest Frame})}{m_{\nu_i}}$$

$$\Rightarrow E_\pi(\text{Lab}) \gtrsim 10^5 \text{ TeV if } m_{\nu_i} \sim 0.05 \text{ eV}$$

Fraction of all π – decay ν_i that get helicity flipped

$$\approx \left(\frac{m_{\nu_i}}{E_\nu(\pi \text{ Rest Frame})}\right)^2 \sim 10^{-18} \text{ if } m_{\nu_i} \sim 0.05 \text{ eV}$$

Since L-violation comes only from Majorana neutrino *masses*, any attempt to observe it will be at the mercy of the neutrino masses.

(BK & Stodolsky)

A reactor experiment can cleanly determine whether $\sin^2 2\theta_{13} > 0.01$, and measure it if it is.

Sensitivity:

Experiment	$\sin^2 2\theta_{13}$
Present CHOOZ bound	0.17
Double CHOOZ	0.03–0.02 (In ~ 2011)
Future "US" experiment (Detectors at ~200 m and ~ 1.5 km)	0.01